



**Fermi National Accelerator Laboratory**

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# **Development and Characterization of New Scintillation Materials for Fiber Tracking and Calorimetry\***

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## Abstract

Several polystyrene-based scintillators have been prepared in the Chemistry Facility of Fermi National Accelerator Laboratory and their light yield, fluorescence, and transmittance have been studied. In addition, emission time distributions were measured and the decay time constants were determined. A radiation damage study was performed in which the samples were irradiated to a total dose of 10 Mrad. After annealing, the intrinsic light yield of the most radiation-hard scintillators had not changed significantly.

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# 1 Introduction

This study is part of the ongoing effort to develop high-rate tracking and calorimetry systems based on scintillating fiber technology. Ultimately, we believe that this technology will yield detectors appropriate for SSC experiments. Our immediate goal is to develop short decay time, highly-efficient plastic scintillators that are resistant to radiation damage.

Plastic scintillators consist of a polymer matrix doped with one or two fluorescent compounds referred to as the primary (dopant) and the secondary (dopant) or wavelength shifter. The corresponding scintillator systems are referred to as binary and ternary scintillators. Ionizing particles passing through the scintillator excite polymer molecules which, in turn, can transfer energy to the primary through the Förster mechanism [1]. In a ternary scintillator, the energy is then transferred to the secondary through the emission and reabsorption of a photon. This process always generates photons of longer wavelength than those that would have been emitted by the excited polymer molecules in the absence of any dopants [2].

Standard plastic scintillators emit in the blue violet region of the light spectrum. This spectral region is significantly affected by radiation-induced damage in the polymer. This damage produces absorption which causes a decrease in the light yield of the scintillator after its exposure to ionizing radiation [3, 4]. The use of new fluorescent compounds emitting in the green/yellow region of the visible spectrum can reduce such light yield losses, since in that wavelength range polymer absorption (coloring) after irradiation is minimal. Compounds such as 3-hydroxyflavone (3HF) and its derivatives [5] exhibit a large Stokes shift between their absorption (350 nm) and emission (530–550 nm) spectra and have already been used [6, 7] to produce radiation hard scintillators. Given an adequate primary dopant, several commercially available green-emitting wavelength shifters can effectively be utilized in plastic scintillator. The fluorescent compounds investigated in this study are listed in Table 1. They were used to prepare various samples of polystyrene-based ternary scintillators emitting in the green/yellow region, and binary scintillators emitting in the blue. In addition, samples of standard blue-emitting plastic scintillators were included to enable the correlation of the present results to previous data. All samples were analyzed before and after exposure to gamma-radiation. The overall performance of these new plastic scintillators is compared to that of the standard blue-emitting plastic

scintillators.

**Table 1.** Fluorescent compounds used in this study.

Compound	$\lambda^a$	Description
pT	360	p-terphenyl <sup>b</sup>
DAT	375	di-t-amyl-p-terphenyl <sup>b</sup>
MOPOM	420	phenyloxazol derivative <sup>c</sup>
OLIGO408	410	bridged oligophenylene <sup>b</sup>
OLIGO415A	415	bridged oligophenylene <sup>d</sup>
BBQ	470	isoquinoline derivative <sup>e</sup>
K27	500	benzoxanthene derivative <sup>f</sup>
DMPOPOP	430	phenyloxazol derivative <sup>g</sup>
3HF	530	3-hydroxyflavone <sup>g</sup>

<sup>a</sup>Wavelength of emission in nm. Available from: <sup>b</sup>Bicron Corp., <sup>c</sup>synthesized by J. M. Kauffman, <sup>d</sup>Exciton Inc. as Exalite 416, <sup>e</sup>Sigma Chem. Co., <sup>f</sup>Hoechst Chem. Co., <sup>g</sup>Aldrich Chem. Co.

## 2 Preparation and Irradiation of Scintillators

### 2.1 Sample preparation

Styrene was first deinhibited through a column and then purified by vacuum distillation. Glass polymerization tubes were cleaned with nitric and sulfuric acids, rinsed with distilled water, and then treated for about 4 hours with a 30% solution of dimethyldichlorosilane in chloroform. Finally, they were rinsed in turn with chloroform, methanol, and distilled water. This treatment builds a hydrophobic Langmuir layer on the walls of the tube which enables the removal of the plastic after polymerization. Appropriate dopants were then added to the polymerization tubes filled with purified styrene and the various solutions degassed with repeated freeze-pump-thaw cycles. The solutions were polymerized in a silicone oil bath at 110 °C for 24 hours, at 125 °C for 48 hours, and finally at 140 °C for 12 hours. The bath temperature was then ramped down to 90 °C at a rate of 10 °C/h. After removal from the oil bath, the tubes were quenched in liquid nitrogen for a fast release of

the plastic rods. The rods were then cut and polished into discs of 2.2 cm diameter and 1 cm thick.

## 2.2 Fluorescent compounds

The new compounds tested as primaries are MOPOM, OLIGO415A (O415), OLIGO408 (O408), and DAT. The term OLIGO is used here to refer to both OLIGO415A and OLIGO408. The secondaries, K27, BBQ, 3HF, and DMPOPOP, have been used in earlier analyses. The new primaries, MOPOM, O415, and O408, were expected to be resistant to radiation since they had been developed as laser dyes and they were known to be stable in that environment [8, 9]. DAT is a derivative of p-terphenyl and should, therefore, also be stable under irradiation. K27 and BBQ were used as secondaries in all the scintillators prepared, except those containing DAT whose emission is blue-shifted with respect to the other primaries. 3HF and DMPOPOP were utilized in the samples doped with DAT. The secondaries were purified by recrystallization from methylene chloride and hexane. The optimum concentration for each primary in styrene was determined by first preparing scintillator samples at concentrations from 0.05% to 2.0% by weight (0.5% to 1.25% in the case of OLIGO408). For each compound, the scintillation light yield from excitation by 1 MeV electrons was measured as a function of concentration. (Details of this measurement are described in Section 4.) The results are plotted in Figure 1. DMPOPOP was added to the DAT optimization run in order to render the fluorescence visible to a standard phototube. The light yield typically saturates at 1% concentration by weight, except that in the case of DAT the optimum concentration is approximately 1.25%. This light-saturation concentration was then chosen for the primaries in the various scintillators. The secondaries were tested at two different concentrations: 0.01% and 0.02%. The light yield was found to be the same for both concentrations.

## 2.3 Irradiations

The samples for radiation damage studies were placed in stainless steel cans and then evacuated for one week to remove all moisture and most dissolved gas from the samples. The cans were then back-filled with dry nitrogen. All samples were irradiated with a  $^{60}\text{Co}$  source at the Nuclear Reactor Labora-

tory of the University of Michigan at a rate of approximately 0.4 Mrad/h to a total dose of 10 Mrad. During the irradiations, the sample temperature was held constant to approximately 5 °C. All the samples developed some coloration during the exposure, some of which disappeared with time when the samples were exposed to oxygen. This phenomenon is referred to as an annealing process in scintillators and is due to the relaxation of excited species that were created during the irradiation. The annealing period for samples of this size is approximately 25 days in air and at room temperature. However, this process can be greatly accelerated if the samples are placed under a pressurized oxygen atmosphere (40 psig.). Under the latter conditions the samples are annealed in about 7 days. For this study, the samples were kept under a 40 psig. oxygen atmosphere for 10 days after their irradiation.

### **3 Transmittance and fluorescence spectra**

Absorbance/transmittance and fluorescence spectra were recorded with a Hewlett-Packard model 8451A diode array spectrophotometer. All absorbance and transmittance measurements used pure (undoped) polystyrene as the reference. The fluorescence spectra were measured using an external Hg lamp whose light was brought into the spectrophotometer by means of a quartz fiber. An excitation wavelength of 254 nm or 313 nm could be selected with the use of bandpass filters. With the 254-nm excitation light, back-surface (BS) excitation measurements were performed. In this geometry, light from the quartz fiber excited the sample surface that faced away from the spectrophotometer collection optics. The sample fluorescence is thus viewed through the sample. A 45° angle of incidence with respect to the surface plane was used. These measurements were performed to monitor the overall scintillation process since, at this wavelength, the polymer molecules are first excited and then energy is transferred to the dopants which, in turn, will fluoresce. For each sample, the fluorescence integrated over all wavelengths was measured. Corrections for fluctuations in the Hg lamp intensity were applied to these data. The results from this measurement are expected to be similar to those obtained using  $^{207}\text{Bi}$  as an excitation source (section 4), since ionizing radiation also excites the polymer which, in turn, transfers part of its excitation energy to the dopants. With the 313-nm light, front-surface (FS) excitation measurements were recorded in which the quartz fiber was



positioned so that the UV light excited the sample surface facing the spectrophotometer optics. In this case, the fluorescence is viewed directly, i.e., not through the sample. (The angle of incidence was also 45°.) These measurements were made in order to monitor any radiation-induced degradation in the dopants independently of any effects on the polymer since, at this wavelength, only the dopants will absorb. Any significant decrease in the fluorescence area after irradiation will indicate that the dopant is degraded under irradiation.

Figures 2-4 present the transmittance spectra (A) before irradiation, (B) immediately after 10 Mrad irradiation, (C) 13 days after irradiation, and (D) 53 days after irradiation of the binary scintillators containing 1% MOPOM, 1% O415A, or 1% O408. For reference, the fluorescence spectrum ( $\lambda_{ex}$  = 254 nm, BS) of the scintillator has also been included. Immediately after irradiation, these blue-emitting scintillators showed a large decrease in light yield. As the spectra recorded at that stage show most of the light emitted by the scintillator was being reabsorbed due to the radiation-induced losses in transmittance. The self-absorption of the emitted light decreased as the annealing process started and the transient species created in the polymer during irradiation disappeared. These severe transmittance losses in the binary scintillators suggested that the addition of a secondary emitting in the green (BBQ or K27) would improve the light yield of these scintillators. Fluorescence spectra using a front-surface 313-nm excitation light of these binary scintillators did not show any significant radiation-induced degradation in the fluorescent compounds. These measurements verified that the light yield losses observed were mainly due to transmittance losses caused by radiation-induced damage in the polymer matrix.

Figures 5-12 give the transmittance spectra for the ternary scintillators studied. Measurements at the four different stages described above were also performed on these scintillators. For reference, the fluorescence spectrum ( $\lambda_{ex}$  = 254 nm, BS) of the scintillator has also been included. After irradiation, the transmittance in the fluorescence region has considerably decreased. Most of the emitted light is being reabsorbed by the scintillator, explaining the loss in light yield. These spectra also indicate that the samples containing BBQ as the secondary dopant exhibit larger absorption than those doped with K27. This difference becomes more evident at longer wavelengths. However, fluorescence spectra ( $\lambda_{ex}$  = 313 nm, FS) of BBQ-doped samples did not suggest any noticeable degradation in the dopant. After the annealing pe-

riod under oxygen, the transmittance improves significantly. Nevertheless, all samples show some residual absorption which decreases the light yield of the scintillator. Among the samples studied, those based on MOPOM as the primary dopant present larger radiation-induced absorption in the region of emission of the scintillator. The DAT+3HF sample shows the least amount of absorption in the region where the secondary fluoresces. At this stage, the BBQ-doped samples have annealed to the same degree as those doped with K27. The last measurements, 53 days after irradiation, show a slight improvement in the transmittance of the scintillators, indicating that a very slow annealing process occurs over a long time frame. For MOPOM-doped samples, the presence of BBQ or K27 makes the scintillator less susceptible to the permanent transmittance losses. For samples containing the OLIGO compounds, the increase in light yield due to the presence of BBQ or K27 is not as great as that observed in the MOPOM-doped scintillators.

## 4 Light yield results

The scintillators were excited by 1 MeV conversion electrons from a  $^{207}\text{Bi}$  source. The scintillation light yield measurements used a Hamamatsu R669 photomultiplier as the photo-detector. This tube has a relatively constant quantum efficiency from 430 nm to 600 nm. The scintillator discs were placed directly on the photomultiplier using immersion oil for optical contact. The pulse height spectra were recorded with a LeCroy qVt multi-channel analyzer and then light yield values obtained from these measurements were corrected for the quantum efficiency variations of the photomultiplier tube over the fluorescence wavelength region of the scintillator studied. The light yield of the scintillators before irradiation, after irradiation, and after annealing are given in Table 2. The last row lists the light yield ( $\equiv 1$ ) from a standard scintillator, 1.25% p-terphenyl + 0.01% DMPOPOP, in order to provide a reference to previously known data. The light yield values as a function of the annealing time are plotted in Figure 13 for blue-emitting scintillators and in Figure 14 for green-emitting scintillators doped with K27.

Before irradiation, the light yield measurements indicate that the new fluorescent compounds produce a scintillator with a higher yield than that measured for the more standard scintillators, except for DAT and MOPOM which provide scintillators with light output similar to that of p-terphenyl.

The OLIGO compounds doped either with K27 or BBQ have up to sixteen percent higher light yield than the standard reference, pT+DMPOPOP. A large decrease in light yield is observed immediately after irradiation in all samples, with the largest effects observed in scintillators containing MOPOM. For ternary scintillators, the light loss is 70–85% for samples with MOPOM, 40–65% for those with OLIGO compounds, and 55–65% for those with DAT. These light yield losses are caused by the radiation-induced absorbance that the scintillator presents in the wavelength range of its fluorescence.

**Table 2.** Light yield before and after 10 Mrad irradiation dose from  $^{60}\text{Co}$  source (in arbitrary units).

SCINTILLATOR <sup>a</sup>	$\lambda^b$ (nm)	Light yield				Ratio <sup>d</sup>
		Before	After	After 13 d <sup>c</sup>	After 53 d <sup>c</sup>	
MOPOM	420	0.90	0.05	0.48	0.56	0.62
MOPOM+0.01%BBQ	470	1.08	0.15	0.72	0.81	0.75
MOPOM+0.02%BBQ	470	1.09	0.18	0.78	0.86	0.79
MOPOM+0.01%K27	500	1.08	0.31	0.85	0.94	0.87
MOPOM+0.02%K27	500	1.08	0.31	0.85	0.96	0.88
O415A	415	1.05	0.56	0.90	1.00	0.96
O415A+0.01%BBQ	470	1.15	0.48	0.98	1.10	0.96
O415A+0.02%BBQ	470	1.16	0.39	1.01	1.13	0.97
O415A+0.01%K27	500	1.10	0.65	0.99	1.09	0.99
O415A+0.02%K27	500	1.13	0.60	1.00	1.11	0.99
O408	410	1.00	0.55	0.86	0.94	0.94
O408+0.02%BBQ	470	1.16	0.39	0.99	1.13	0.97
O408+0.02%K27	500	1.10	0.65	1.01	1.11	1.01
DAT	375	0.83	0.18	0.52	0.53	0.64
DAT+0.01%DMPOPOP	430	0.98	0.35	0.80	0.85	0.87
DAT+0.01%3HF	530	0.97	0.46	0.72	0.78	0.81
pT	360	0.96	0.24	0.47	0.48	0.50
pT+0.01%DMPOPOP	430	1.00	0.58	0.81		

<sup>a</sup>Fluor concentrations are by weight, the concentrations of primaries are 1% (1.25% for DAT and pT). <sup>b</sup>Wavelength of peak emission. <sup>c</sup>First 10 days in oxygen and the rest in the air. <sup>d</sup>After 53 d/Before.

After annealing, the light yield of the scintillators increases. At thirteen days into the anneal, the light loss is : 20–30% for MOPOM, 10–15% for OLIGO, and 20–25% for DAT. At this stage, however, some radiation-induced absorbance still remains. After 53 days, the light loss is 10–25% for samples with MOPOM, 0–4% for OLIGO and 10–20% for DAT. The light yield of the scintillators has increased approximately 10% over the previous measurements. However, the transmittance plots after 53 days of irradiation do not reflect such significant improvement. The increase could be caused by further “hidden” annealing in the polymer [7] which the transmittance plots do not show since the polymer is doped. The best scintillators are OLIGO415A+K27 and OLIGO408+K27. After 53 days of annealing, their light yield is essentially the same as for the unirradiated samples. The OLIGO415A+BBQ and OLIGO408+BBQ samples seem to be slightly affected by radiation, with light loss of about 3% (our measurement error is of the same order). MOPOM+K27 and DAT+DMPOPOP give results similar to the pT+DMPOPOP sample. The light yield values for the DAT+3HF sample, listed in table 2, include contributions from both 3HF fluorescence and DAT fluorescence. As Figure 12 shows, when the DAT+3HF sample is excited with UV light some of the DAT fluorescence is not absorbed in the sample and can thus reach the spectrophotometer’s photo-detector along with fluorescence from 3HF. The same would be true for the  $^{207}\text{Bi}$  measurements, i.e., the photomultiplier tube views both DAT and 3HF fluorescence. After irradiation, the DAT light will be more severely attenuated than that of 3HF. This will give rise to a larger light yield decrease for the DAT+3HF sample. Using fluorescence data (BS, 254-nm excitation light), the DAT contribution to the signal after annealing has been estimated to be about 15%, whereas before the sample was irradiated, its contribution to the total signal was 18%. The majority of the signal loss is still due to a decrease in the number of 3HF fluorescence photons leaving the sample.

Both the total area under the fluorescence spectra (using 254-nm excitation light) and the peak position in the pulse height spectra from  $^{207}\text{Bi}$  excitation measure the light yield of the scintillators. Both measurements agreed to within a few percent, except for the annealed samples, OLIGO+BBQ and OLIGO+K27, for which the fluorescence spectra measure 15% more light (normalized to the appropriate unirradiated sample) than with the photomultiplier.

Immediately after irradiation, the samples containing the OLIGO com-

pounds and a secondary dopant exhibited phosphorescence when excited by room light. The time constant for this phosphorescence was on the order of minutes. However, this phenomenon was only observed in the OLIGO samples containing a wavelength shifter. No phosphorescence was detected in samples doped with only the OLIGO derivatives. The phosphorescence disappeared in the annealed samples. The existence of a triplet state at relatively low energy has been reported for other similar bridged oligophenylenes [10]. The current observations suggest that the presence of the wavelength shifter favors, under irradiation, the population of this triplet state.

## 5 Emission time distributions

Emission time distributions were measured in the setup shown in Figure 15. A  $^{22}\text{Na}$  source excites the scintillator sample and the  $\text{BaF}_2$  trigger crystal. The geometry is such that only single photons from the scintillator reach the PM2 photomultiplier (Hamamatsu assembly H4022). The  $\text{BaF}_2$  crystal coupled to PM1 photomultiplier (Hamamatsu assembly H3177) provides the START signal for the LeCroy qVt operating in the time mode. Single photons detected in PM2 generate STOP signals. The examples of measured time distributions are given in Figures 16 and 17 for OLIGO408 and OLIGO408+K27 scintillators. The broad peak at about 17 ns in Figure 16 is attributed to “after-pulsing” of the photomultiplier tube and was observed in a similar experiment[11]. We assumed that the emission time probability distribution can be described by two (or one) exponential decays: (the details of the shape of scintillation pulse have recently been reviewed [12].)

$$E(t) = \frac{\frac{e^{-t/\tau_1}}{\tau_1} + \frac{R}{\tau_2} e^{-t/\tau_2}}{1 + R} \quad (1)$$

$$E(t) = \frac{1}{\tau_2} e^{-t/\tau_2} \quad (2)$$

Where  $\tau_1$  and  $\tau_2$  are the decay constants and  $R$  is the ratio between the two components. We assumed a gaussian time error with a standard deviation  $\sigma_t$  and a gaussian distribution *BUMP* accounting for the “after-pulsing” peak. The resulting time distribution is then:

$$P(t) = \int_0^\infty E(t') \frac{1}{\sqrt{2\pi}\sigma_t} e^{-(t-t')^2/2\sigma_t^2} dt' + \text{BUMP} \quad (3)$$

By fitting the above distribution to the data we can determine the parameters  $\tau_1$ ,  $\tau_2$  and R. They are given in Table 3 and curves representing the fits are overlaid on the data shown in Figures 16 and 17. The green/yellow scintillators were fitted with a one exponential decay, (eq. (2)), and the blue binary scintillators: MOPOM, OLIGO415A and OLIGO408 were fitted with two exponential decays, (eq. (1)).

**Table 3.** Parameters of the emission time distributions.

SCINTILLATOR	Parameters of emission time		
	Decay time		R
	$\tau_1(\text{ns})$	$\tau_2(\text{ns})$	slow/fast
MOPOM	$2.7 \pm .1$	$12.1 \pm 1.1$	$0.31 \pm .07$
MOPOM+0.02%BBQ		$11.7 \pm 0.2$	
MOPOM+0.02%K27		$11.2 \pm 0.2$	
O415A	$2.5 \pm .2$	$10.6 \pm 0.4$	$0.98 \pm .12$
O415A+0.02%BBQ		$12.2 \pm 0.2$	
O415A+0.02%K27		$11.1 \pm 0.2$	
O408	$2.5 \pm .1$	$11.2 \pm 0.8$	$0.38 \pm .06$
O408+0.02%BBQ		$12.8 \pm 0.2$	
O408+0.02%K27		$10.8 \pm 0.1$	
DAT+0.01%3HF		$7.60 \pm 0.1$	

## 6 Conclusions

The MOPOM-doped scintillators are not as bright as those doped with the OLIGO compounds. In the binary scintillators, before irradiation the OLIGO derivatives have 10–15% higher light yield than MOPOM; after annealing they have approximately 80% greater light yield than MOPOM. In the ternary scintillators, the MOPOM-doped samples have improved in light output because of the added wavelength shifter, but the performance of the OLIGO-doped samples is still superior. The possible degradation under irradiation of MOPOM has been explored. However, the fluorescence measurements do not indicate any significant loss of this compound. In contrast, dilute solutions of MOPOM in cyclohexane or styrene monomer exhibited good resistance to radiation damage [13].

The samples doped with BBQ, regardless of the primary dopant used, exhibit larger transmittance losses after irradiation than those containing K27. Nonetheless, after the annealing period their light yield is again similar to that of the K27-doped scintillators.

The radiation-induced hidden absorption of polystyrene affects all the samples, since this absorption can compete with energy transfer between the primary and the secondary. As this absorption anneals, the secondary can absorb more light from the primary, thus giving rise to a brighter scintillator. This is the reason for the slow improvement of the scintillators over a long time period. This effect is also the explanation for the relatively large drop in light output after annealing for the DAT+DMPOPOP and the DAT+3HF samples. Both these samples show little induced absorption in the wavelength region of their fluorescence so transmittance losses cannot explain the drop in light yield. In the region of the DAT fluorescence, however, there is a great deal of polymer absorption after the irradiations and after the anneal. This absorption competes with energy transfer between the DAT and the two secondaries. Since the DMPOPOP absorption at 350 nm is stronger than that for 3HF, the light loss due to "hidden" absorption is somewhat less for the DAT+DMPOPOP sample than for the DAT+3HF sample.

Most of the new scintillators have light yields equal to or higher than the standard scintillator pT+ DMPOPOP (the exceptions are: MOPOM and DAT). Annealed OLIGO+K27 scintillators do not exhibit any light yield loss after irradiation to a 10 Mrad dose from a  $^{60}\text{Co}$  source. OLIGO+BBQ seems to be slightly affected and shows a 3% loss. The blue scintillators OLIGO408 and OLIGO415A exhibit a 4% loss. OLIGO408 is significantly faster than OLIGO415A in the sense that it has a much smaller slow/fast component ratio.

All these measurements, however, were made with 1-cm thick samples, so light loss due to transmittance loss is a small effect (except for the case of PS+MOPOM). Since after irradiation all samples, except DAT+3HF, showed transmission losses in the region where the secondary dopant fluoresces, the light yield of most of the scintillators will decrease as the sample size increases. Although OLIGO+K27 is the best scintillator in this study, DAT+3HF could still be a better choice if long fibers were to be used.

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## Figure Captions

Figure 1. Scintillation light yield as a function of dopant concentration in percent by weight: (A) OLIGO415A, (B) DAT, (C) OLIGO408, and (D) MOPOM.

Figure 2. Transmittance spectra for the scintillator with 1% MOPOM: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 3. Transmittance spectra for the scintillator with 1% OLIGO415A: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 4. Transmittance spectra for the scintillator with 1% OLIGO408: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation, and fluorescence spectrum (E) before irradiation.

Figure 5. Transmittance spectra for the scintillator with MOPOM+BBQ: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 6. Transmittance spectra for the scintillator with MOPOM+K27: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 7. Transmittance spectra for the scintillator with OLIGO415A+BBQ: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 8. Transmittance spectra for the scintillator with OLIGO415A+K27: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 9. Transmittance spectra for the scintillator with OLIGO408+BBQ: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 10. Transmittance spectra for the scintillator with OLIGO408+K27: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 11. Transmittance spectra for the scintillator with DAT+DMPOPOP: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 12. Transmittance spectra for the scintillator with DAT+3HF: (A) before, (B) immediately after, (C) 13 days after and (D) 53 days after 10 Mrad irradiation; and fluorescence spectrum (E) before irradiation.

Figure 13. Light yield of blue-emitting scintillators as a function of annealing time. The light yield before and immediately after irradiation is plotted at  $t = -5$  and  $t = 0$  days.

Figure 14. Light yield of green/yellow-emitting scintillators as a function of annealing time. The light yield before and immediately after irradiation is plotted at  $t = -5$  and  $t = 0$  days.

Figure 15. Experimental setup for decay time measurements.

Figure 16. Time distribution of OLIGO408 scintillator compared with the fit.

Figure 17. Time distribution of OLIGO408+K27 scintillator compared with the fit.

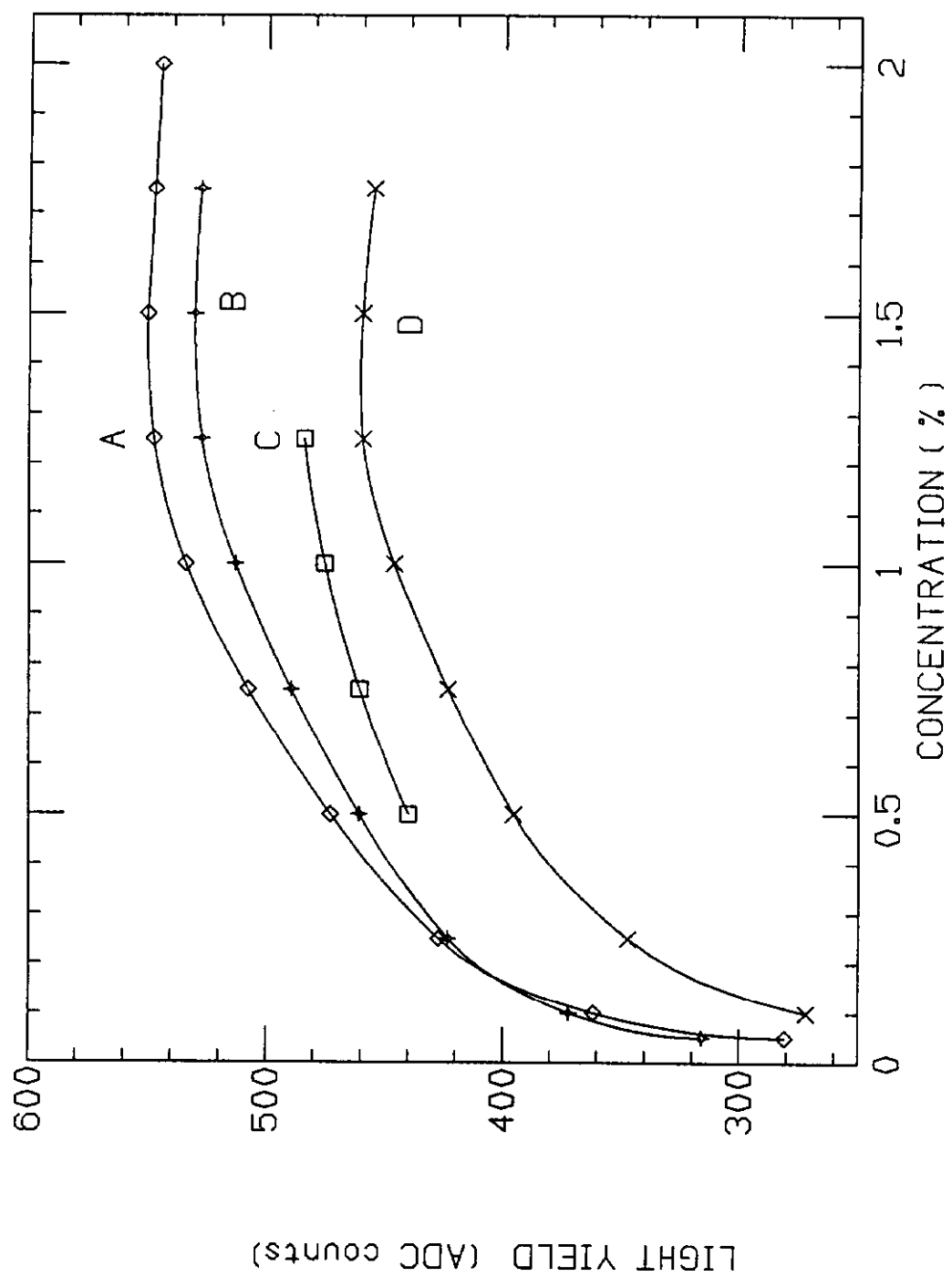


Figure 1

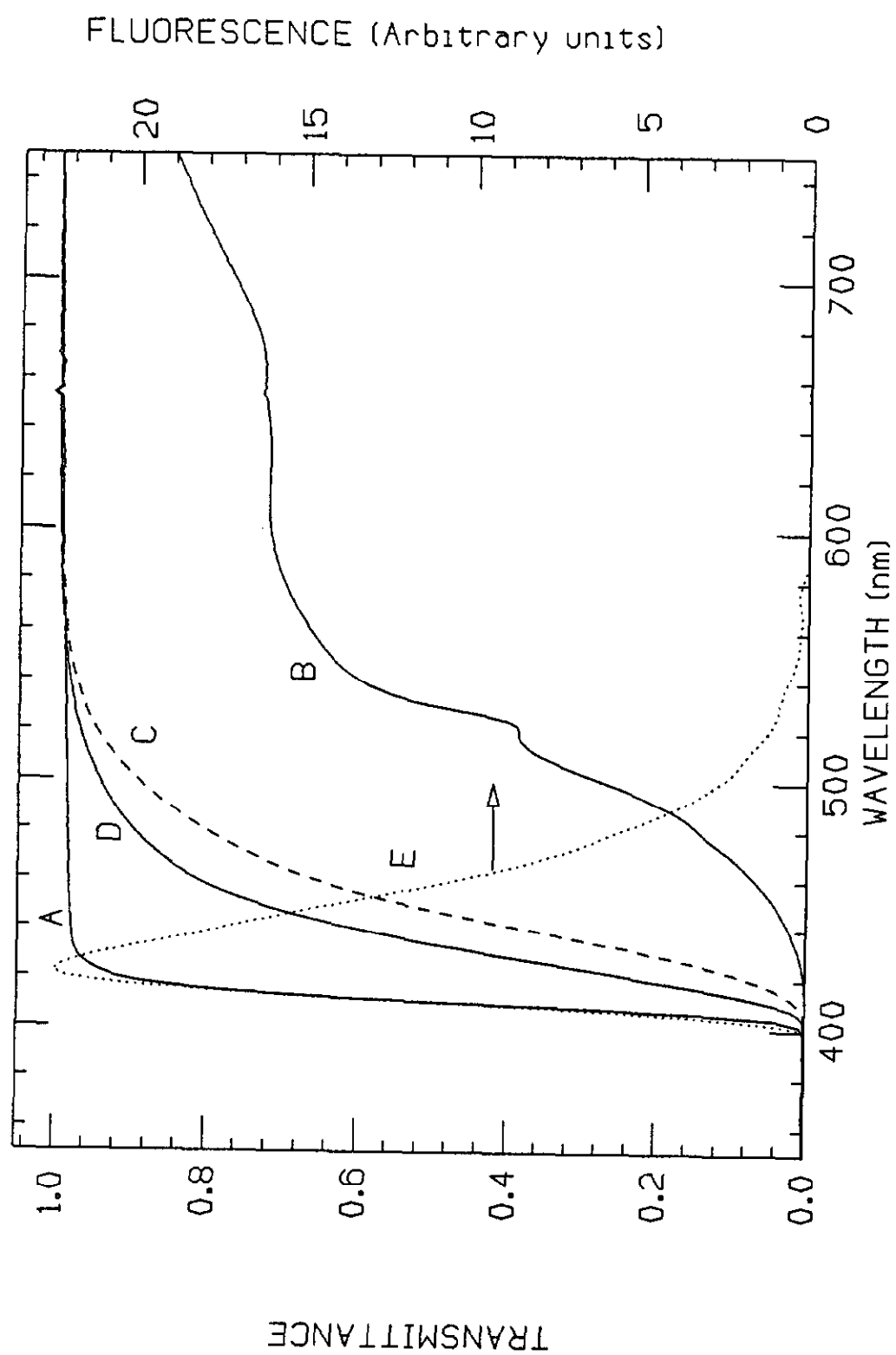


Figure 2

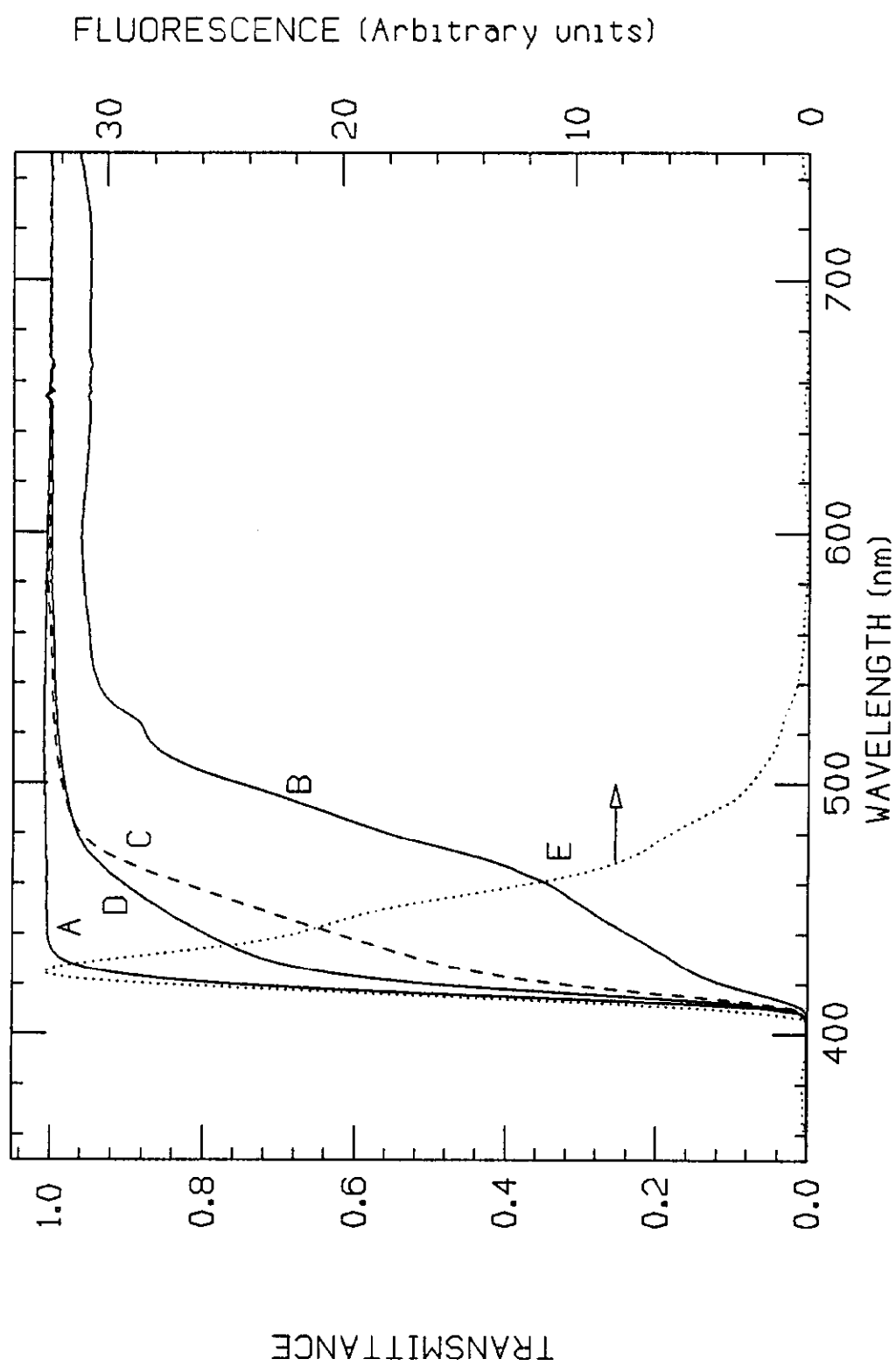


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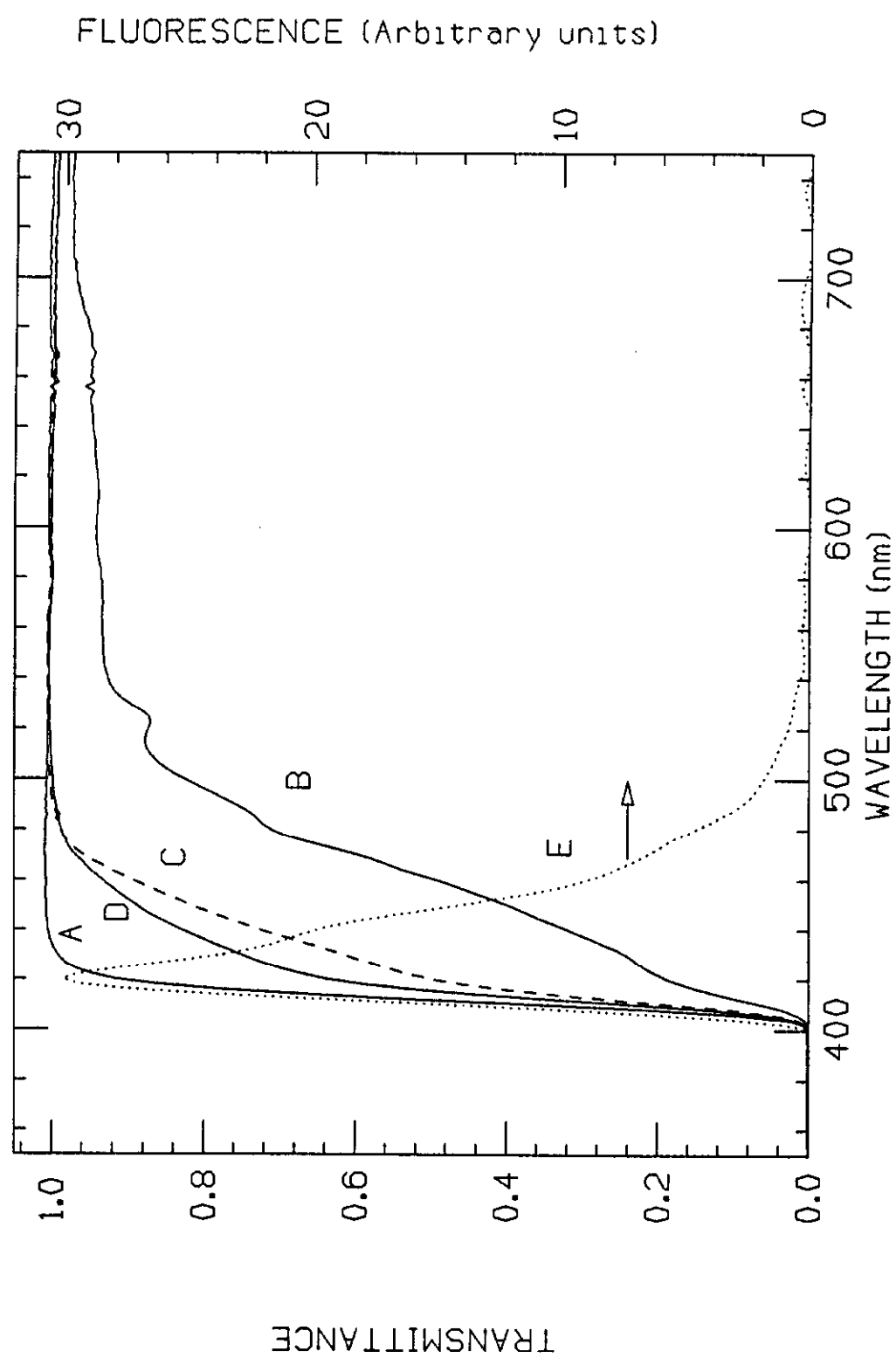


Figure 4

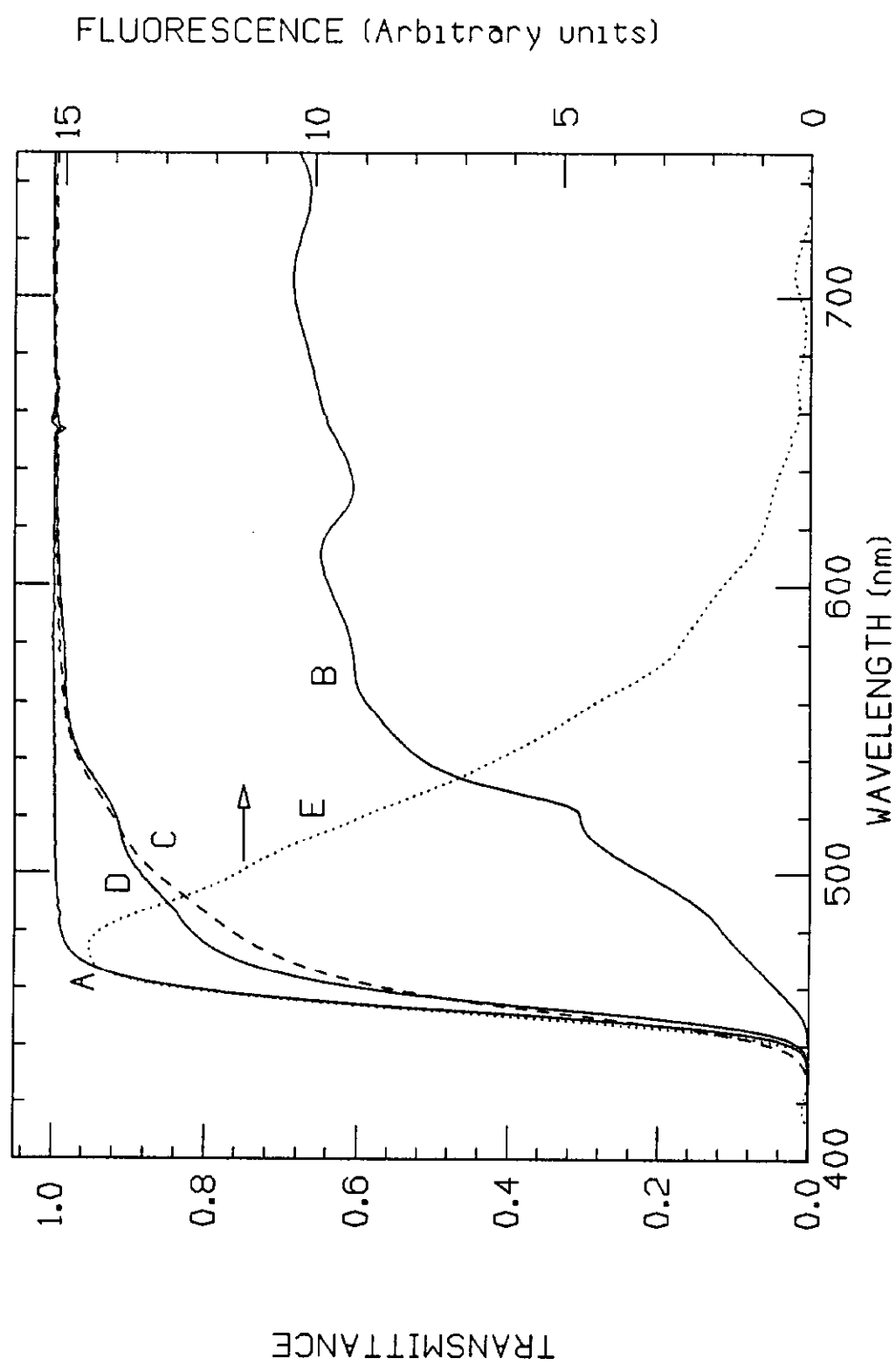


Figure 5



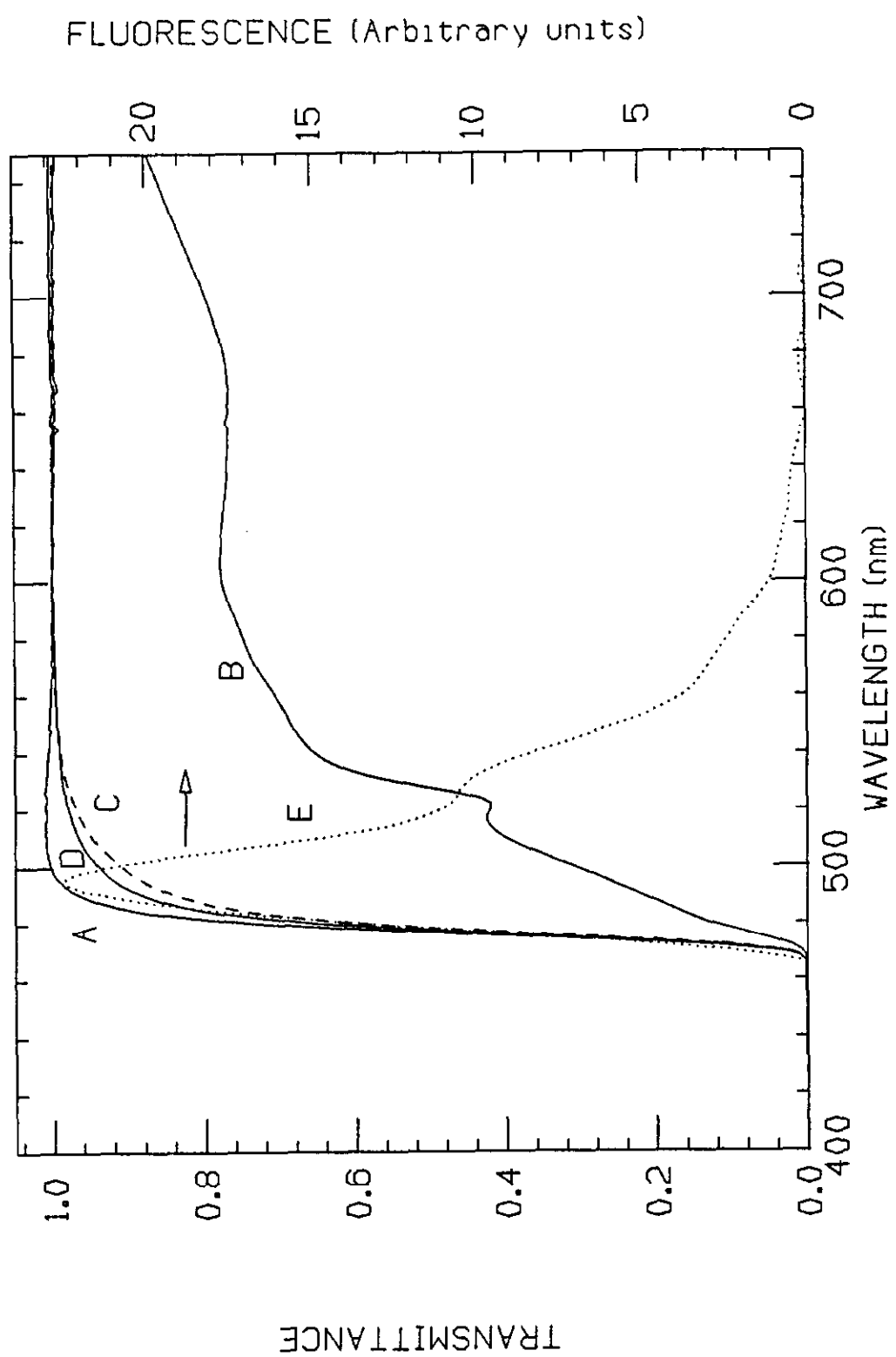


Figure 6

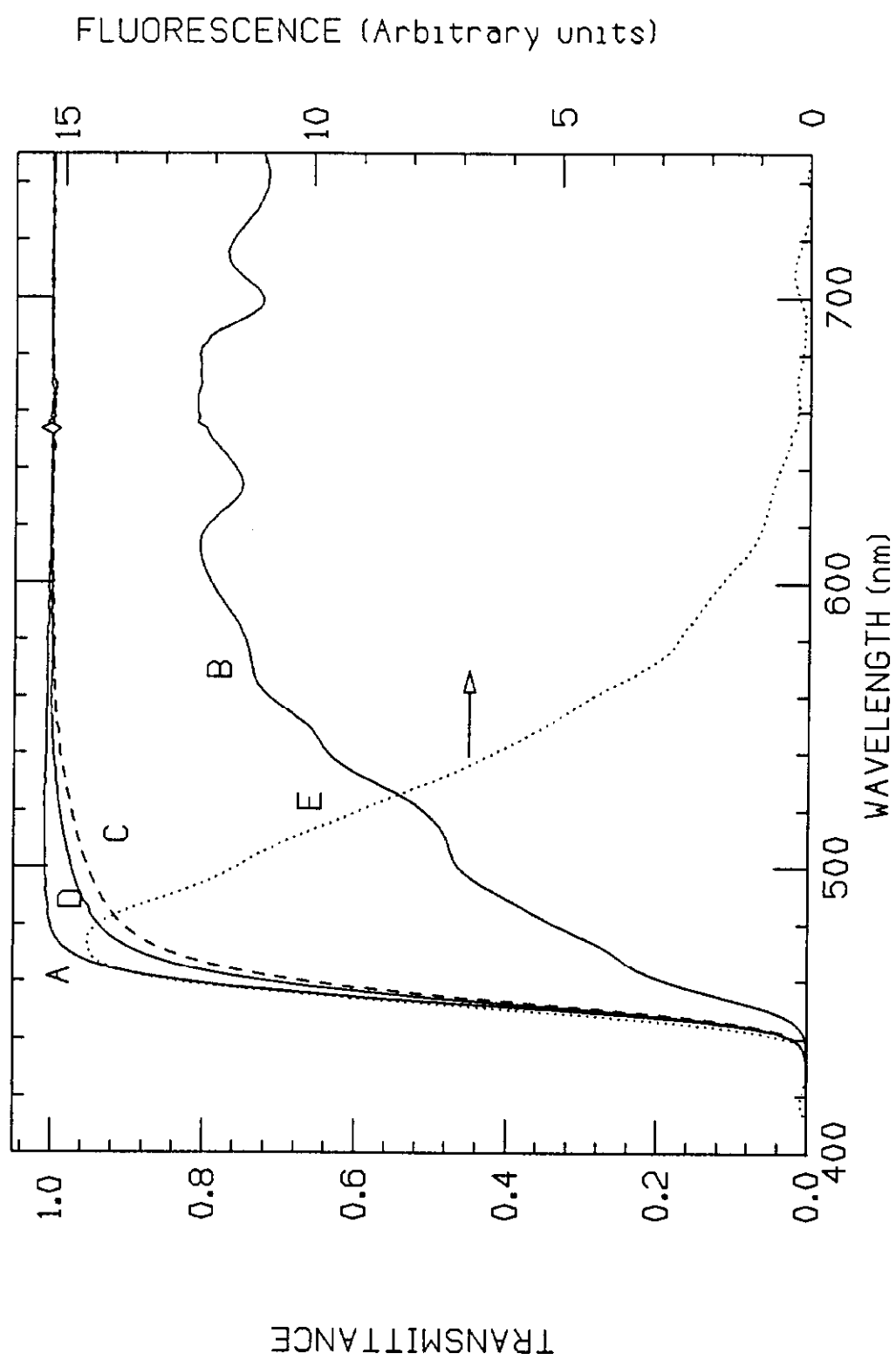


Figure 7

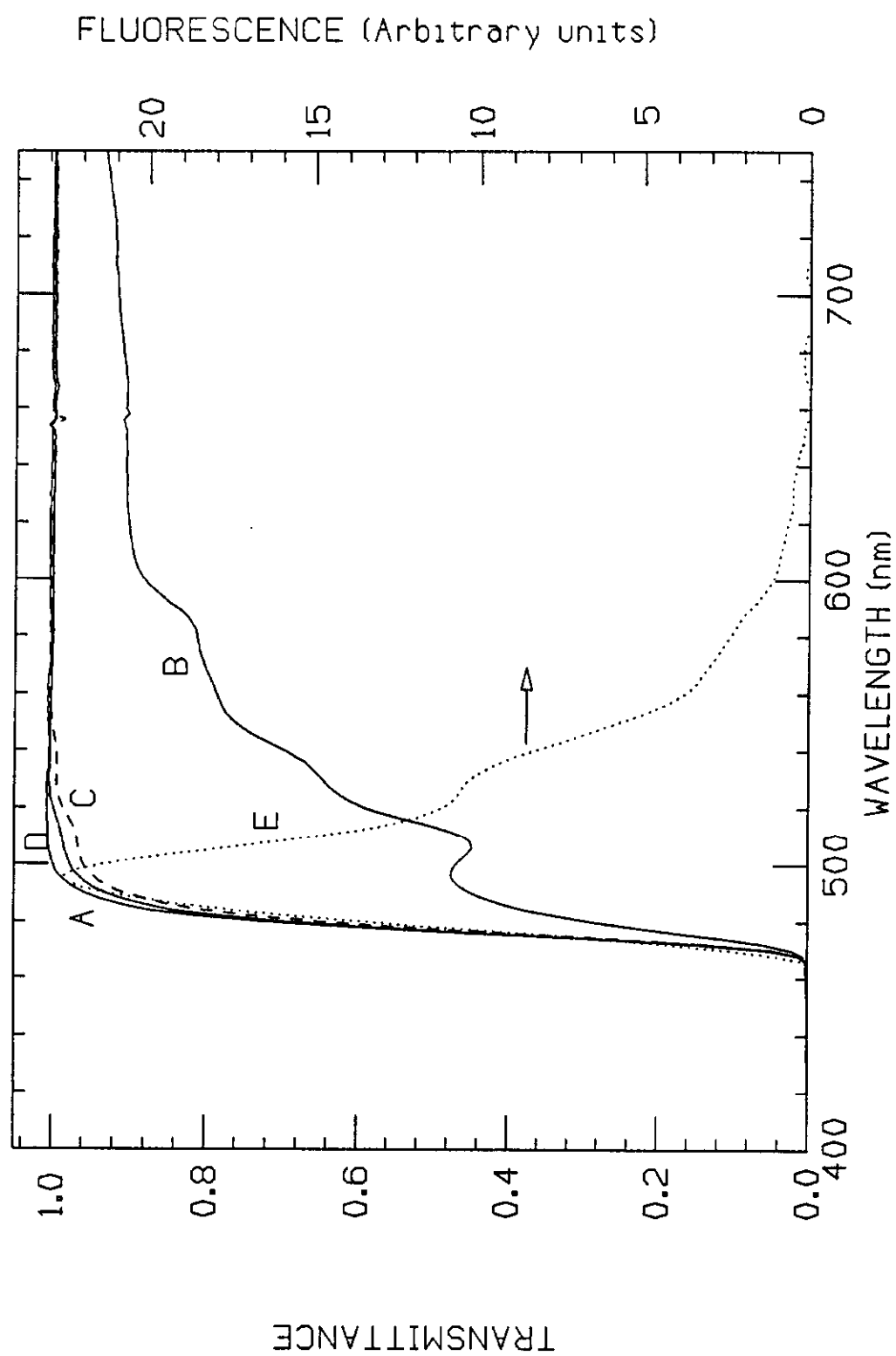


Figure 8

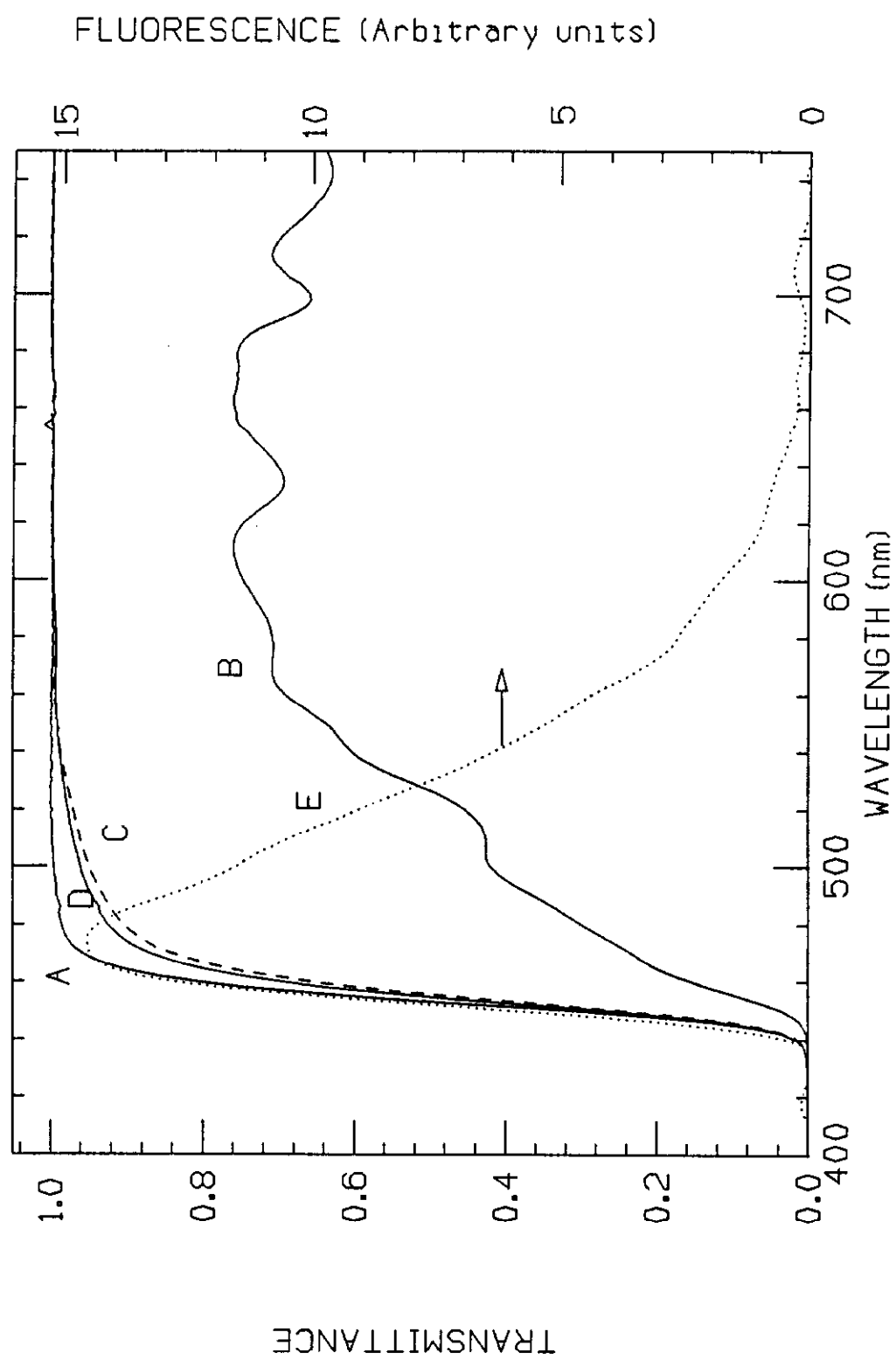


Figure 9

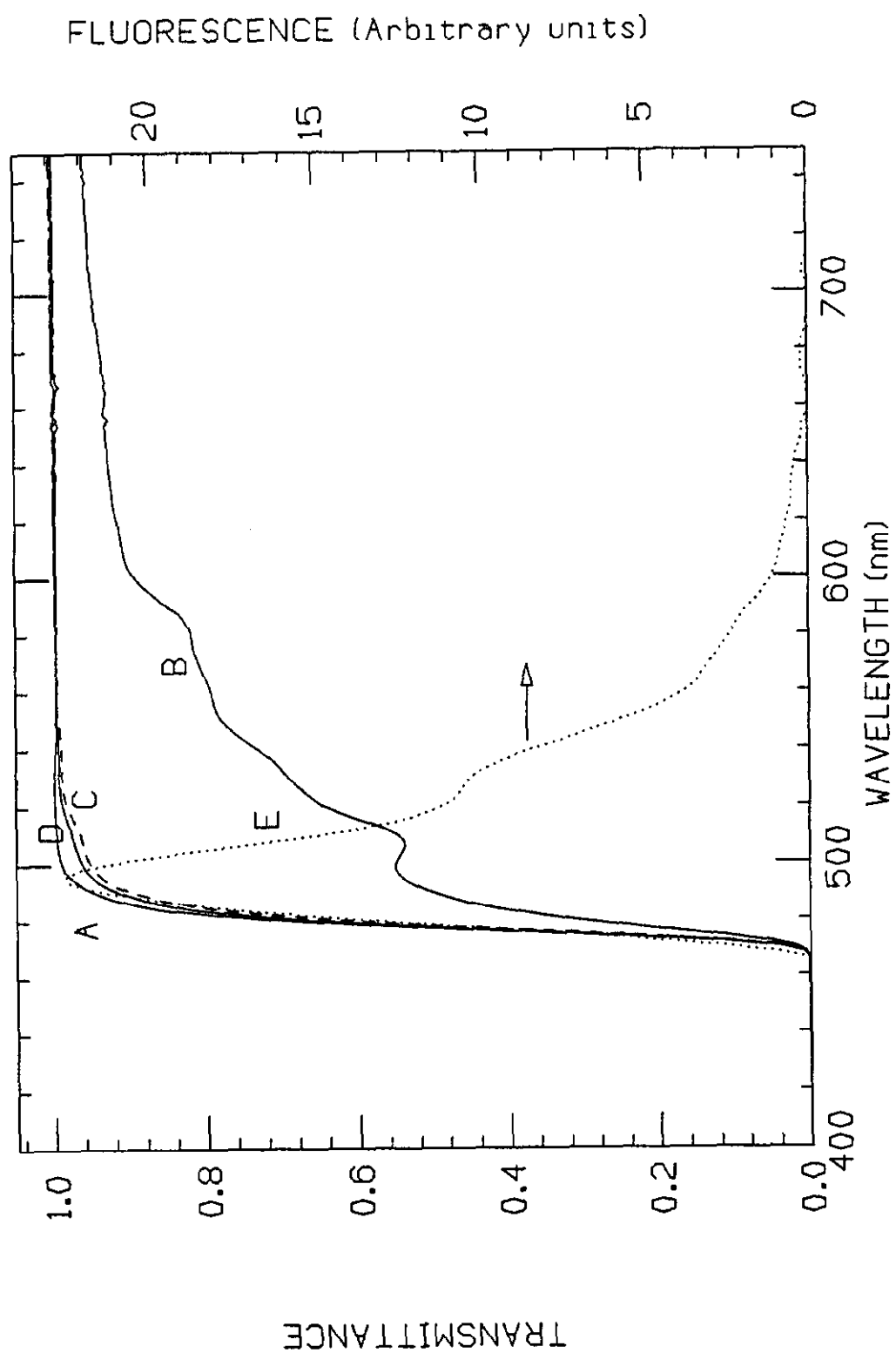


Figure 10

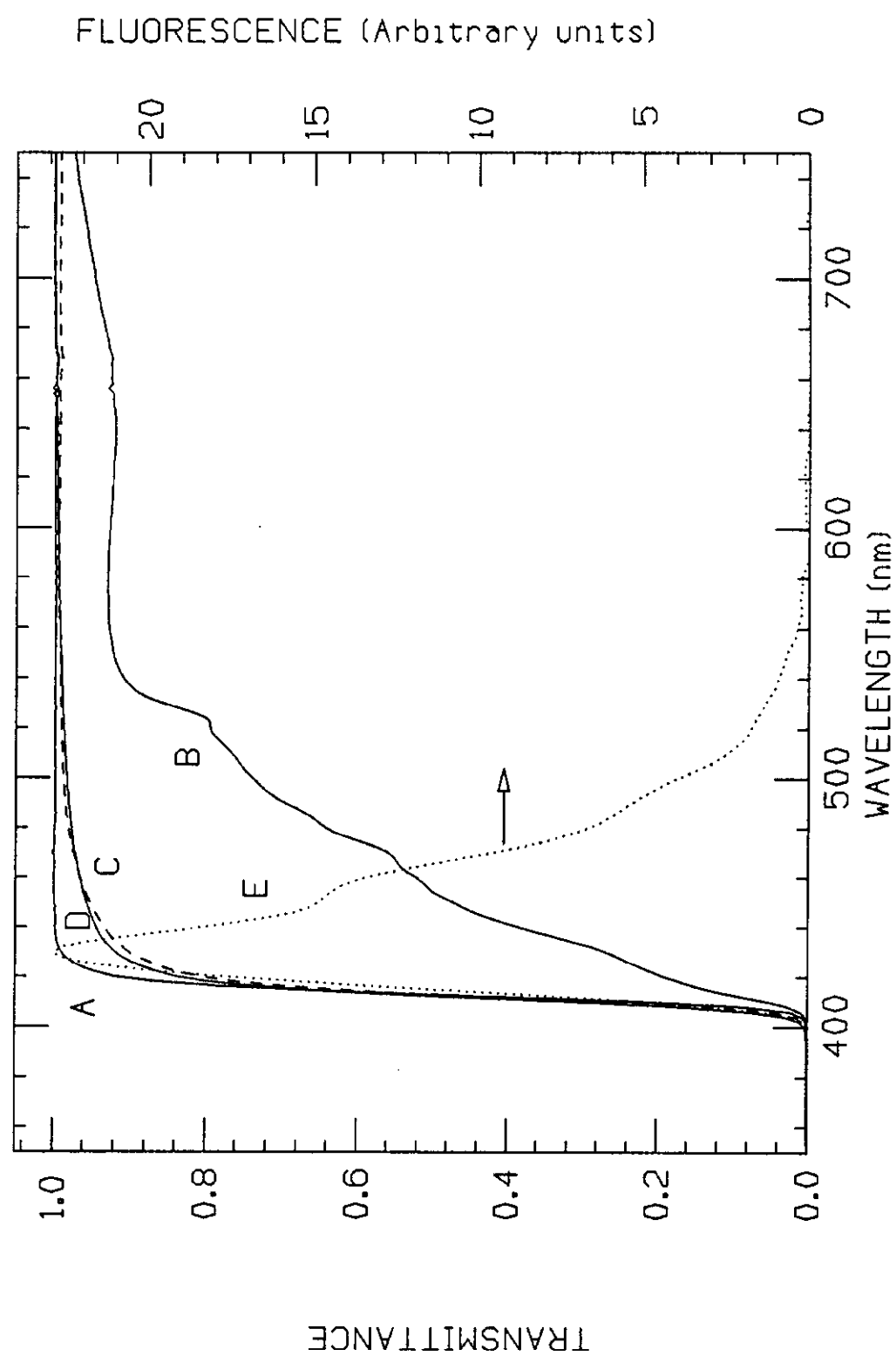


Figure 11

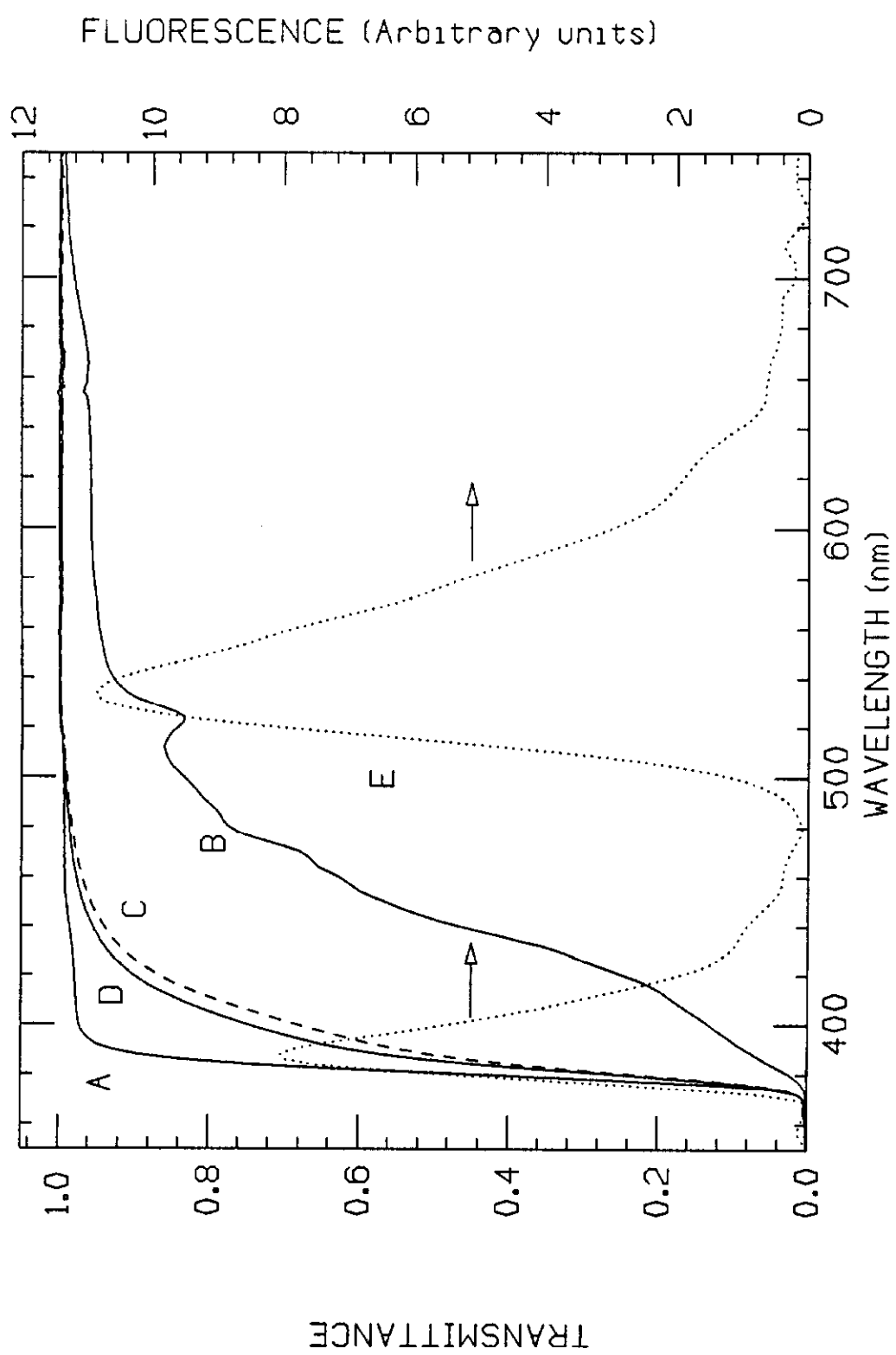


Figure 12

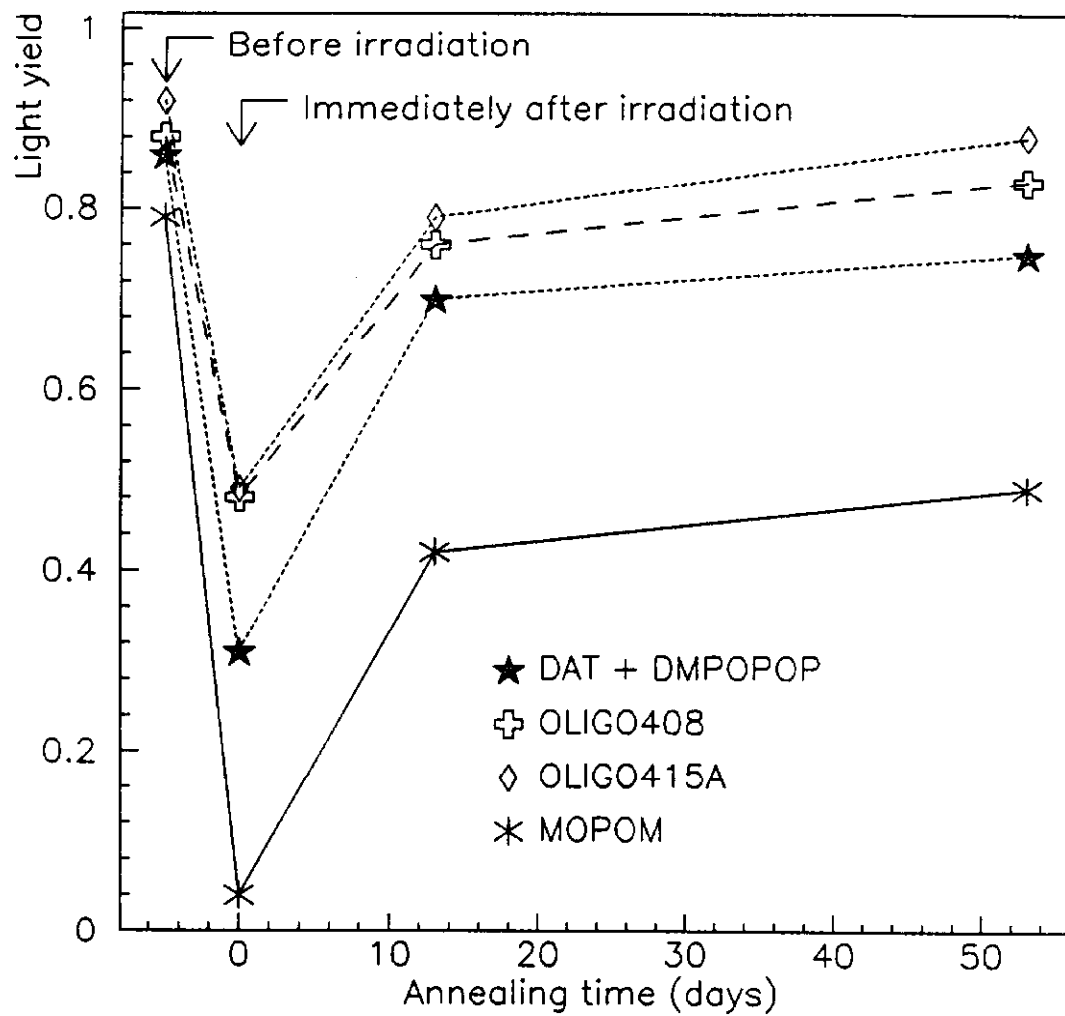


Figure 13



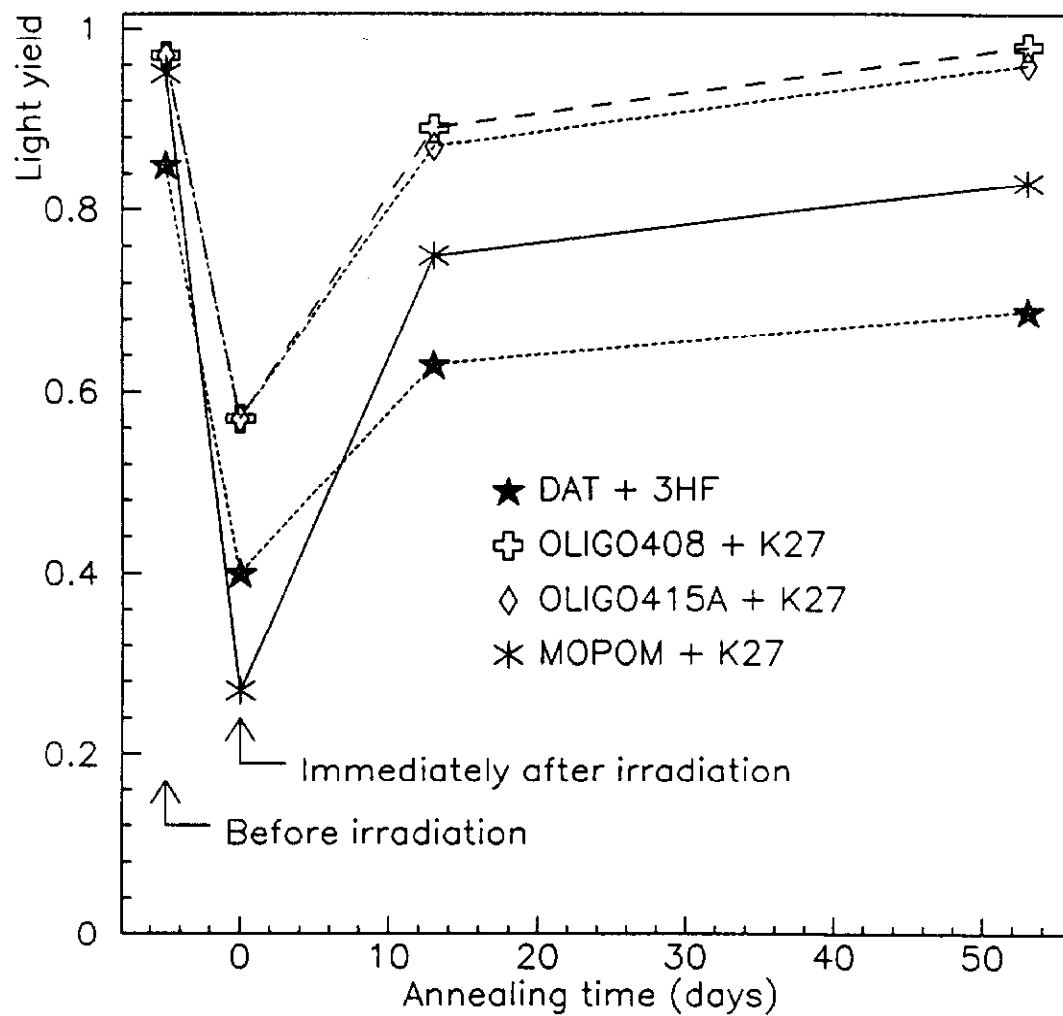


Figure 14

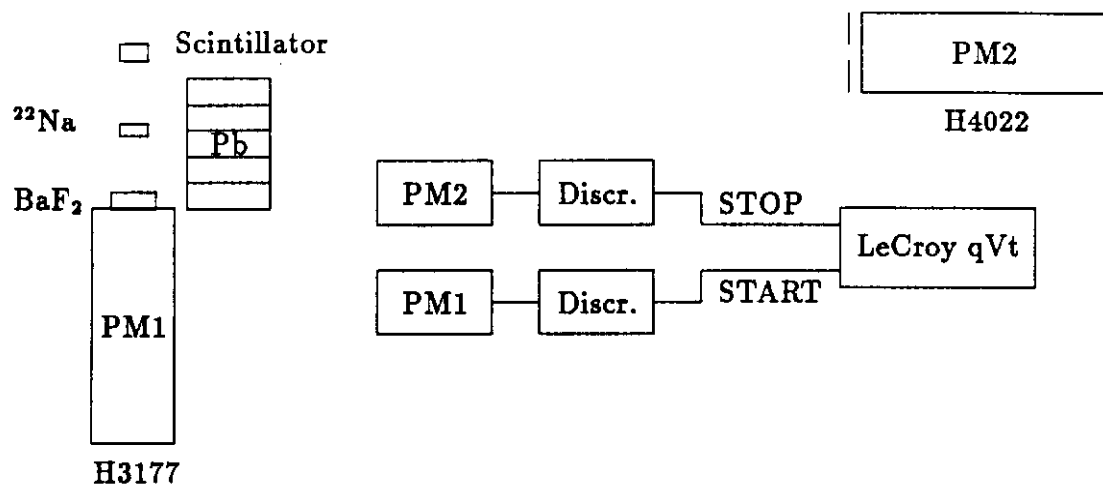


Figure 15

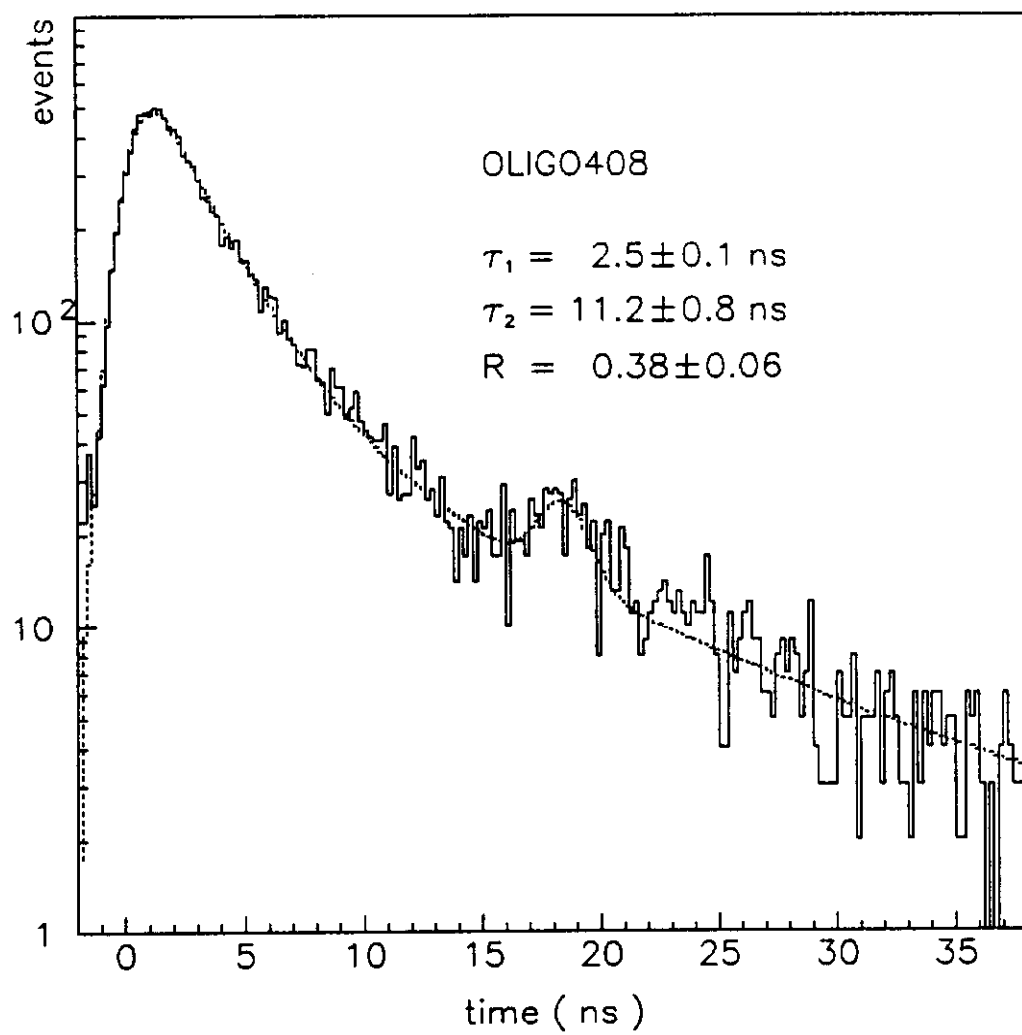


Figure 16

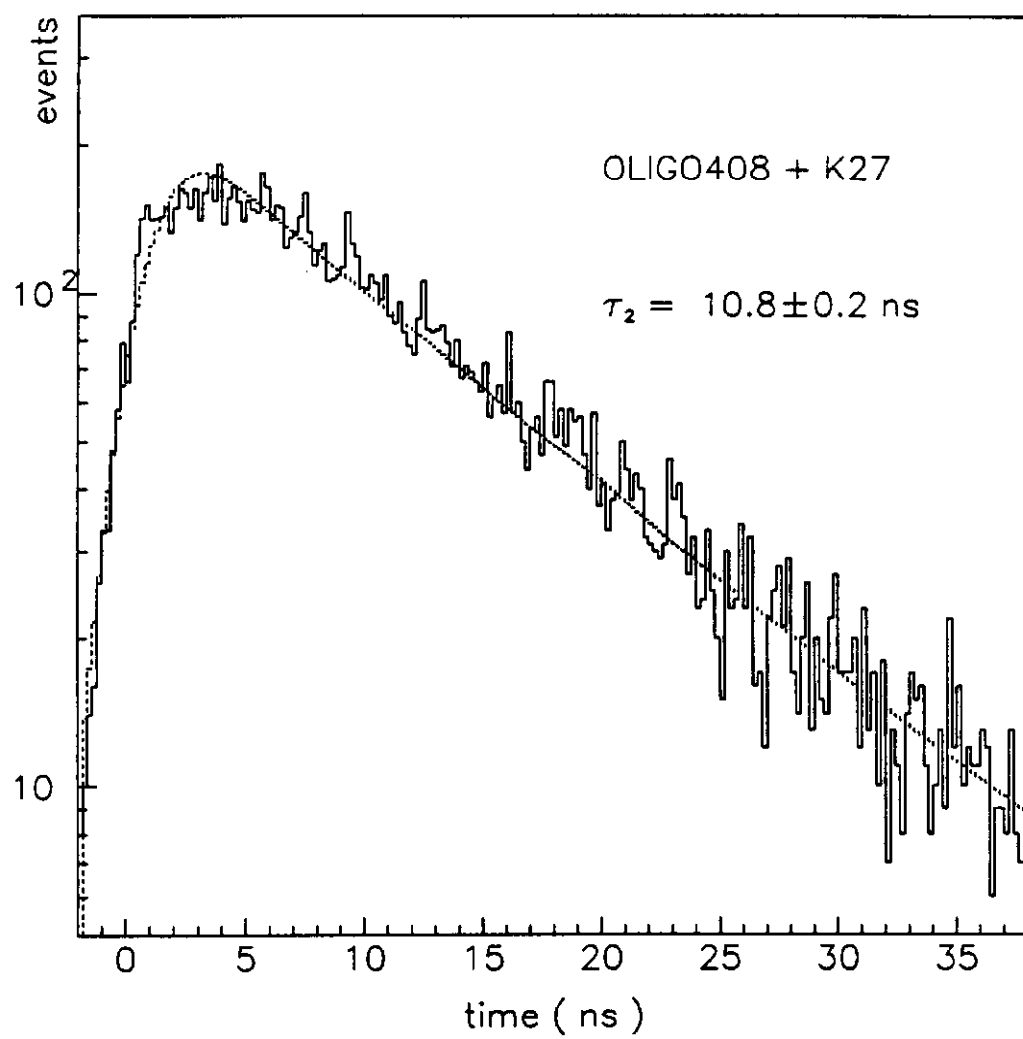


Figure 17